Influencing Variables, Precision and Accuracy of Terrestrial Laser Scanners

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Key words: terrestrial laser scanning, influencing variables, systematic errors, accuracy

SUMMARY

Terrestrial laser scanning has become an additional technique in geodetic applications. Since several years, laser scanning is used for applications in cultural heritage. The recent developments of laser scanners widened the field of applications to engineering geodesy. Hence, the requirement regarding the knowledge of laser scanners and their strengths and weaknesses has to be improved, especially from a geodetic point of view.

A comprehensive investigation of one terrestrial laser scanner, the "Imager 5003" of Zoller+Fröhlich, including different influencing variables will be discussed. Thereby, the main focus lies on analyzing the distance and angle measurement system. But also other systematic effects are mentioned like trunnion axis error, eccentricity of the scan centre, collimation axis error, and horizontal axis error.

Despite the importance of investigating and analysing each component of laser scanners separately, most users are only interested in resulting accuracies of single points or of derived objects. For satisfying these requirements, both mentioned accuracies will be derived.

ZUSAMMENFASSUNG

Terrestrisches Laserscanning hat sich als eine ergänzende Technik für geodätische Anwendungen etabliert. Während seit einigen Jahren Laserscanning vorwiegend für Aufgaben im Bereich des Kulturerbes eingesetzt wurde, ist nun auch aufgrund technologischer Weiterentwicklungen der Einsatz im der Bereich der Ingenieurvermessung möglich. Die Eigenschaften von Laserscanner bezüglich ihrer Stärken und Schwächen muss dafür jedoch untersucht werden, insbesondere von einem geodätischen Standpunkt aus.

Eine umfassende Untersuchung des Laserscanners „Imager 5003" von Zoller+Fröhlich wird vorgestellt. Verschiedene Einflussgrößen werden genannt, wobei der Schwerpunkt auf der Untersuchung der Distanz- und Winkelmessung liegt. Aber auch andere Faktoren wie Taumelfehler, Exzentrizität des Scanzentrums, sowie Ziel- und Kippachsenfehler werden behandelt.

Obgleich die Untersuchung von Einzelkomponenten der Laserscanner wichtig ist, ist der gemeine Anwender mehr an Genauigkeiten interessiert. Um diesem Aspekt zu genügen, wird eine Genauigkeit sowohl für den Einzelpunkt als auch für Objekte, die aus mehreren Einzelpunkten abgeleitet werden, angegeben.

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1. INTRODUCTION

In the market, terrestrial laser scanners of several companies are available (e.g. HDS Leica-Geosystems, Riegl, Optech, Mensi, Zoller+Fröhlich, IQVolution). A direct comparison between laser scanners is difficult because of their specific construction (e.g. deflecting principle, distance measurement system) and defining / characterising parameters (e.g. scan density / sampling interval, scan rate). The recent developments of terrestrial laser scanners opened a wide field of applications to them. The use of laser scanners is increasing. But in contrast to traditional geodetic instruments (e.g. total stations, levels, GPS), most of the available laser scanners are not well known regarding accuracies and systematic errors. If one uses terrestrial laser scanner for high precision applications (e.g. engineering surveying), an investigation and an analysis are essential.

A comprehensive investigation procedure regarding several parameters was carried out for the "Imager 5003" of Zoller+Fröhlich. Some of these results are discussed in this paper.

2. DISTANCE MEASUREMENT SYSTEM

The distance measurement system of the "Imager 5003" of Zoller+Fröhlich is based on the phase measurement principle (Mettenleiter et al., 2003). An initial range is determined by means of a coarse frequency. A fine frequency improves this range within few millimetres. Thereby, two coarse frequencies can be chosen. The unambiguousness for an initial range differs from 25.2 m (named measurement mode "close") to 53.5 m (named measurement mode "far"). The "Imager 5003" can operate both in "scanning mode" and in "static mode". Using the "scanning mode" means that the deflecting unit (a rotating mirror) is moving. In contrast, the deflecting unit in the "static mode" is not rotating and can be aligned manually. Some important aspects can be gained in the "static mode" like accuracy, precision and long-run behaviour.

The examinations were carried out on the calibration track line and at the laboratories of the Institute of Geodesy and Photogrammetry. The calibration track line has a length of nearly 52 m. Distances are provided by an interferometer within an accuracy of a thousandth millimetre (one micron). These distances are of a factor thousand more accurate than the measured distances of the laser scanner. Thus, they can be treated as nominal distances.

2.1 Static Mode

In several data series with different intervals (one, five and ten metres), the distance measurement system was investigated in the "static mode". For this purpose, the laser beam was aligned towards a target in the way that the laser beam ran horizontally (deflecting mirror and target were nearly in the same height). A white paper with a black scale was used as target.

By examination the “static mode”, a set of thousand measurements (single shots) for each range was stored (measurement frequency of 125 kHz, default noise). Based on these measurements mean distances and the corresponding nominal distances were compared (defined as accuracy). Also, the differences between minimum and maximum distance within all thousand measurements for each measurement position were calculated (defined as precision).

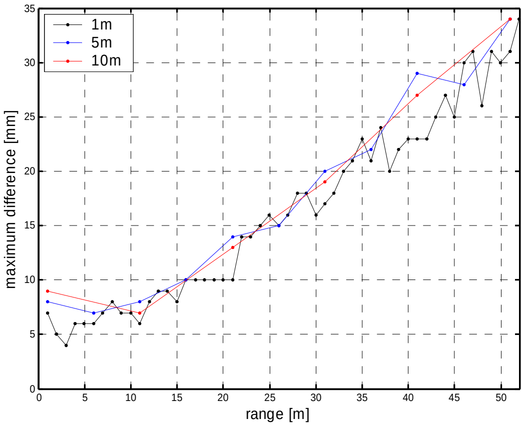

Figure 1a: Differences between minimum and maximum distance (within all thousand measurements)

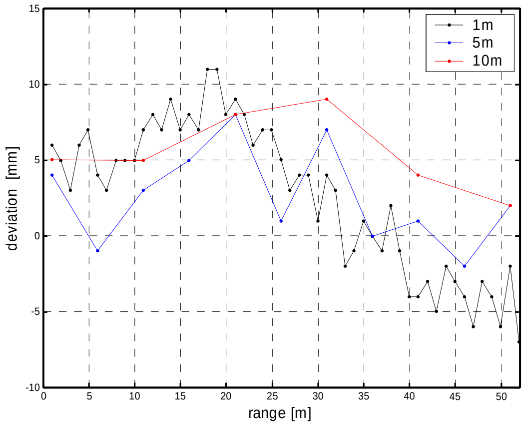

Figure 1b: Deviations between measured distances (mean values) and nominal distances

In figure 1a, the differences between minimum and maximum distance of all thousand measurements within each measurement position can be seen. The differences between minimal and maximal measured distances are increasing in correlation with the range. In farer distances, differences of more than ten millimetres are visible. They exceed more than 30 millimetres at a maximum range of 50 metres.
The differences between nominal distances and measured distances (mean distance of all thousand measurements) are shown in figure 1b. It can be seen that the deviations start at a value of nearly five millimetres, increase up to a maximum value by a range of nearly twenty metres and decrease. Some systematic effects can be assumed caused by calibration parameters, e.g. addition constant (approx. five millimetres) and scale factors (with positive and negative signs).

2.2 Scanning Mode

Analogue to the investigations in the “static mode”, the “scanning mode” was examined on the calibration track line. Spheres with a white colour surface were scanned in intervals of one metre. The diameters of the spheres, which were calibrated before, are at about fifteen centimetres (sphere 1) and twelve centimetres (sphere 2). All results are based on the “scanning mode” named “super high” (other “scanning modes” can be chosen, named “high”, “middle” and “preview”). This “scanning mode” has the highest point density. Depending on the point cloud, the centres of the spheres (centre points) were derived. The centre points were computed in two methods. In the first method, both the centre points and the diameters were estimated (“free” diameter). In the second method, the diameters were fixed and only

the centre points were computed ("fixed" diameter). Then, the horizontal distances to the centre points could be compared to the nominal distances.
In figure 2, the differences between the distances to the centre points and the nominal distances are shown. The following conclusions can be drawn:

- An addition constant (approx. 4 mm – according to "static mode") can be seen in all graphs (confirmed by independent investigations).
- The results with fixed diameters are better than the results with "free" diameters.
- The deviations increase up from fifteen metres.

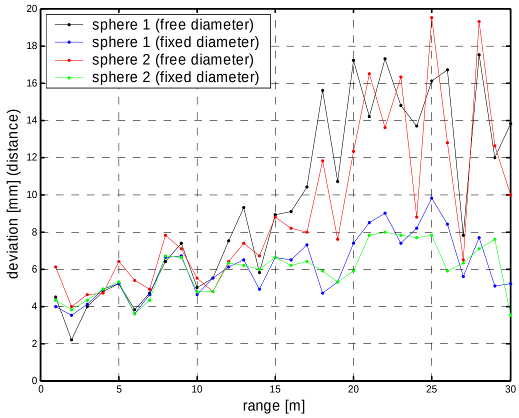

Figure 2 : Deviations between the distances to the centre points and the nominal distances

The centre points were calculated by an iterative adjustment. The point with a significant distance to the surface of the sphere (e.g. five millimetres or more) was eliminated. The adjustment was repeated, until either all points lay within a maximum distance to the surface of the sphere (e.g. five millimetres) or the unknowns (co-ordinates of the centre points) changed below a limited value (e.g. one tenth of millimetres).

2.3 Long-run Behaviour

Of further interest is the behaviour of the distance measurement system within a long observation period. For investigating the long-run behaviour, the distances were logged over a time period of two hours by an observation interval of one minute in the "static mode". Like mentioned before, the result of each distance measurement is a derived mean value of thousand measurements (single shots). The examination was made in different ranges. One range was close and represents an internal reference plate (white colour) of the laser scanner (distance approx. 0.1 m). The other range is at about 5.4 m and was surveyed with two different targets (white paper with black scale and only a white paper).
In figure 3a, the results of two data series to the reference plate are shown. In figure 3b, the results to different targets (a white paper and a white paper with a black scale) in a distance of approx. 5.4 m are drawn. It can be seen that the mean values (of thousand single shots) are changing within several millimetres. A correlation of the accuracy between temperature (in the interior of the laser scanner), intensity of the reflected laser beam and the distance can be assumed. Astonishing is that the oscillation in distance is higher at the white paper than at the white paper with the black scale.

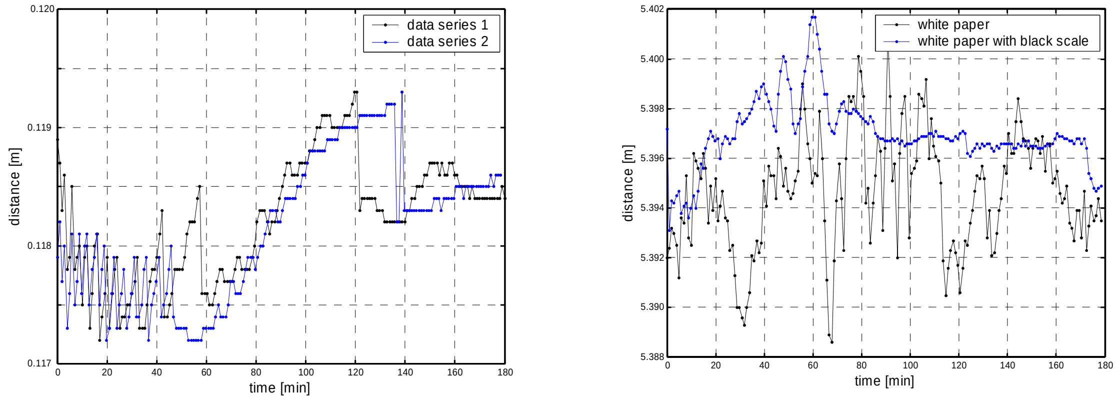

Figure 3a + 3b: Derived mean values (of thousand single shots) within an observation period of two hours (in different distances)

3. ANGLE MEASUREMENT SYSTEM

In the "scanning mode", two spheres were used as targets. These spheres were moved along the calibration track line which has a well known trajectory. The centres of the spheres were derived by an adjustment procedure relative to a local scanner reference frame. After transformation of this local reference frame into the reference frame of the calibration track line, the residuals can be used for interpretations of the distance and angle measurement system. The up direction corresponds to the vertical direction and the transversal direction corresponds to the horizontal direction. The residuals in these two directions are (nearly) independent of the distance accuracy and can be used for investigating the angle measurement system. The distance accuracy of the laser scanner influences only the longitudinal direction.

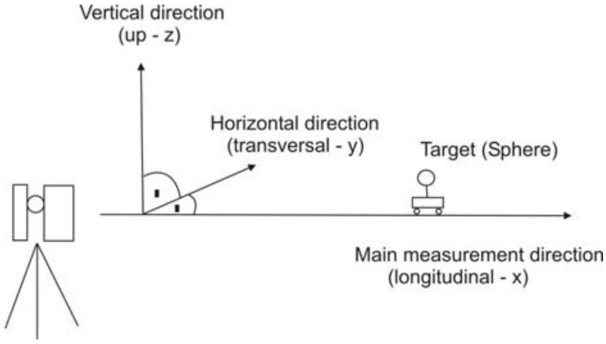

Figure 4 : Reference frame of the calibration track line

The declaration of an angular value is not applicatively. For short ranges, the metric value results in a large angular value (e.g. 1 mm corresponds to 64 mgon for a distance of 1 m). For long ranges, the distance accuracy of the laser scanner decreases (spheres / targets should lie within twenty metres).

3.1 Horizontal and Vertical Direction

The residuals in horizontal and vertical direction allow a conclusion regarding the accuracy of the horizontal and vertical angles. In figure 5a and figure 5b, the residuals in horizontal direction and in vertical direction are listed. The results are based on the “scanning mode” named “super high”. The residuals are less than one millimetre up to fifteen metres and much better than the distance accuracy.

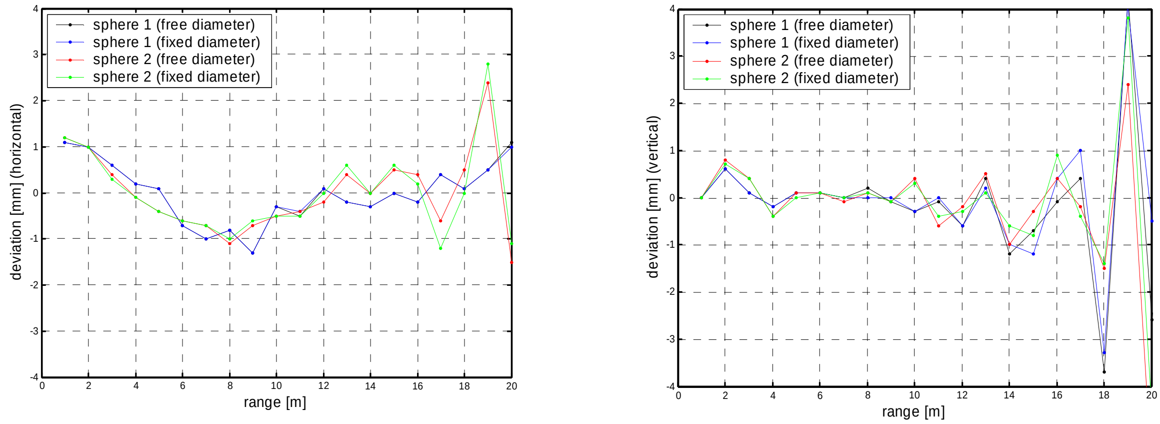

Figure 5a + 5b: Residuals in horizontal and vertical direction

4. FURTHER INFLUENCING VARIABLES

By considering a laser scanner like a total station, one has to care about instrumental errors. Some of them are

- trunnion axis error,
- eccentricity of scan centre,
- angle of incidence as well as surface properties,
- collimation axis error, and
- horizontal axis error.

The trunnion axis error, the eccentricity of scan centre, the angle of incidence, and surface properties were investigated in detail (Schulz and Ingensand, 2004a, 2004b).
The examination of the collimation axis error and the horizontal axis error were already done. For that purpose, spheres were scanned in two faces analogue to observations made with total stations. With the derived horizontal and vertical angles to the targets, the collimation axis error and the horizontal axis error can be estimated (Deumlich and Staiger, 2002). The collimation axis error is at approx. 3 mgon, whereas the horizontal axis error is at approx. 30 mgon. Reasons for the big error of the horizontal axis error lie in the accuracy and limits of levelling the laser scanner (precise levels and compensators are necessary and recommended for a precise levelling of the laser scanner).

5. ACCURACY OF LASER SCANNER DATA

5.1 Single Point Accuracy

The accuracy of one single point can be derived by the accuracy of Cartesian co-ordinates (*x*, *y*, *z*). By calculating the centres of the spheres, the adjustment algorithm produces an $m_{0\ a\ posteriori}$. This value can be interpreted as variance of one single Cartesian co-ordinate.

One obtains the accuracy of one single point with

$$m_P = \sqrt{3} \cdot m_{0\,\text{a posteriori}}.$$

The results are at about 2 mm up to 7 mm. This seems plausibly because of a distance accuracy of approx. 5 mm in distances up to twenty metres.

5.2 Accuracy of Objects (Spheres)

The accuracy of derived objects (using the mentioned spheres) can also be derived by the accuracy of Cartesian co-ordinates (*x*, *y*, *z*). One obtains the accuracy with

$$m_O = \sqrt{m_X^2 + m_Y^2 + m_Z^2}.$$

The single components can be interpreted as

- distance accuracy (longitudinal direction): m_X
- angle accuracy in horizontal direction (transversal direction): m_Y
- angle accuracy in vertical direction (up direction): m_Z

In figure 6, the 3D-accuracies of the centre points of spheres are shown. The accuracy lies within nearly 5 mm up to fifteen metres. Therewith, the accuracy of derived objects (containing thousands of points) is much better than the accuracy of one single point.

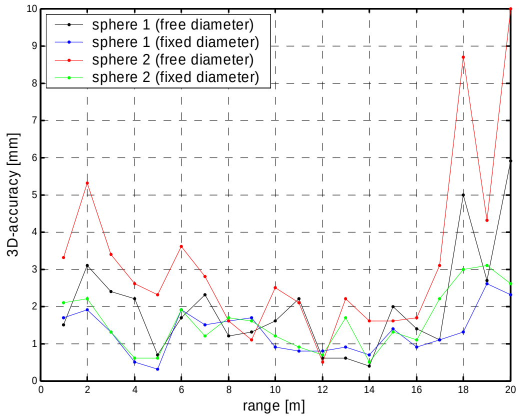

Figure 6 : 3D-accuracy of derived objects (spheres)

6. CONCLUSION

A comprehensive investigation of the “Imager 5003” of Zoller+Fröhlich was discussed. The distance measurement system and the angle measurement system were examined in detail. Further, accuracies regarding single components (distance and angle measurement system), single points and objects were given. In combination with previous investigations of other components (e.g. trunnion axis error, eccentricity of scan centre), the scanner can be judged regarding application area and achieving accuracies.

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BIOGRAPHICAL NOTES

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